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Dr. William Brunk
Office of Space Science and Applications
Lunar and Planetary Programs
NASA Headquarters, Code SL
Washington, D. C.

Dear Dr. Brunk:

This is the final report on NASA Contract No. NASr-65(17) (IITRI Project W6139). The contract began June 1, 1966 and ran to an extended termination date of July 31, 1967.

1. INTRODUCTION

The purpose of the research carried out under this contract was to determine the reason for the disagreement among various estimates for the abundance of water vapor in the atmosphere of Venus. Two approaches to the problem were used: (1) a direct investigation of the water vapor abundance using the 9400 Å and 8200 Å bands, and (2) a study of CO_2 absorption bands at different wavelengths to search for a possible variation in the continuous opacity of the planet's atmosphere. Significant progress was made in both areas, but a definitive answer to the basic problem has not yet been reached. Observations made by other workers during the contract period have led to new inconsistencies that await resolution. A summary of the results of our research is given below followed by a review of the current status of the problem. The report concludes with recommendations for further studies.

2. WORK PERFORMED

2.1 Water Vapor

The spectrum of Venus was recorded in the region of the 9400 Å water vapor band during periods of favorable positive and negative Doppler shift. Reduction of the spectrograms revealed three lines near 9700 Å on the red-shifted series of plates that appeared to show slight asymmetries. However, the absence of similar evidence on the other (blue-shifted) series of spectrograms and the marginal quality of the observations did not permit an unequivocal conclusion to be drawn regarding the presence of Venus water vapor lines.

To provide a set of standards for this work, a series of solar spectra encompassing both the 9400 Å and 8200 Å bands was obtained with the McMath Solar Telescope at Kitt Peak. The lines that had been chosen for use in the 9400 Å region appeared to be unblended, but one line in the 8200 Å region (8176.975 Å) was found to have a weak redward companion (at 8177.42 Å) that would interfere with any attempt to look for a planetary line Doppler-shifted to longer wavelengths. This is the only line of the list suggested by Heyden et al. (<u>Ap. J. 143</u>, 595 (1966)) that was found to be a possible source of confusion in such observations.

Finally, several spectra of Venus in the 8200 Å region were obtained at Kitt Peak in April, 1967, near the time of maximum blueward shift. The best of these plates showed a weak companion to the 8189 Å water vapor line, but no other Doppler-shifted companions. It was therefore suggested that the 8189 Å line was a solar absorption normally hidden behind the much stronger telluric water vapor line that falls at this wavelength. These results have been submitted for publication (see accompanying preprint).

2.2 Carbon Dioxide

The triad of bands appearing near 1.5μ in the spectrum of Venus has been analyzed in some detail. It was found that the abundance of gas derived from individual lines in these bands was a strong function of the line strength. Using a theoretical curve of growth, this behavior is difficult to understand if the local pressure has the commonly assumed value of about one atmosphere (Chamberlain, <u>Ap. J. 141</u>, 1184 (1965)). However, Chamberlain's (op. cit) application of radiative transfer theory to the problem of line formation in a scattering atmosphere provides a very reasonable explanation for the observations. The significance of this result is obvious in that it requires that all determinations of abundances must be made with some kind of scattering model if they are to be placed on an absolute scale.

A qualitative application of this approach was made to the question of the abundance of water vapor. Since the various investigators have used bands differing in strength by several orders of magnitude, they should obtain very different results for the water vapor abundance. Until very recently, however, the results have all been very similar (about 60 microns precipitable water) suggesting that they cannot be mutually consistent. This argument was presented as part of a paper entitled "Chemical Abundances in Planetary Atmospheres" at the Symposium on the Origin and Distribution of the Elements in Paris, May 10, 1967 (preprint attached).

The primary motivation behind the study of the CO_2 bands was a search for the possible presence of a wavelength dependence in the atmospheric opacity. No evidence for such a dependence was discovered, but the strong dependence on the line intensity referred to above could have masked a small change in atmospheric opacity.

3. CURRENT STATUS OF VENUS WATER VAPOR ABUNDANCE DETERMINATIONS

While this research was in progress, four new determinations of the water vapor abundance were reported in the literature:

a) Belton and Hunten, using a pulse counting scanner, detected a companion to the 8189 Å line that exhibited both a correct positive and negative Doppler shift (Ap. J. 146, 307 (1966)). They also suspected a companion to the 8193 Å line and suggested an abundance $\leq$125 microns.

b) Spinrad and Shawl confirmed the Belton-Hunten result using conventional photographic methods (Ap. J. 146, 328 (1966)) and derived an abundance of 60 microns.

c) Connes et al. reported observations at high resolution in the 1-2μ region of the spectrum which failed to show any sign of water vapor in the atmosphere of Venus, setting an upper limit of 20 microns (Ap. J. 147, 1230 (1967)).

d) Kuiper obtained low resolution scans of the 1.4μ water vapor band in the spectrum of Venus from an aircraft at 44,000 feet and derived an abundance of about 0.5 microns (private communication).

The first three of these new reports provided part of the stimulus for the re-investigation of the 8200 Å region described in Section 2.1. If the result reported there is correct, and the principal evidence for water vapor on Venus at 8200 Å is in fact a solar line, then there is an immediate compatibility with the new determinations at longer wavelengths. The matter may not be so simple, however. In a rebuttal to this interpretation of their work, Hunten, Belton, and Spinrad have stated that detection of 60 microns of precipitable water at 8200 Å may be consistent with the very much lower values found at longer wavelengths since the latter results were based on an assumed pressure for the atmosphere of Venus that Hunten et al. feel is a factor of 10 too low. As they point out, this could mean that the abundance derived by Kuiper is also too low by this factor. Moreover, they note that the work on water vapor in the atmosphere of Mars has not indicated that the Doppler shifted line at 8189 Å is any stronger than the line at 8176 Å, which would be the case if the former line consisted of a blend of a solar absorption and a planetary water vapor line. Hunten et al. conclude that there may be a general consistency in results obtained at all wavelengths, a consistency that permits the presence of roughly 50 microns of precipitable water above some level within the clouds on Venus.

While this may be correct, the arguments are still not convincing. Even granting Kuiper an underestimate of a factor of 10, the abundance resulting from his observations would be 10 microns at most, a figure well below that favored by Hunten et al. The Mars observations are not conclusive because Schorn et al. (Ap. J. 147, 743 (1967)) ignored the presence of the weak telluric line at 8177.42 Å (see Section 2.1) in making their analysis. This line would increase the strength of a red-shifted companion to λ8176, thereby making it appear as strong as the blend of a solar and planetary line at 8189 Å. Only the blue shifted spectra would serve as a valid test, and it is not clear that this restriction was made in the comparison. Finally, Kuiper reports substantial amounts of water on Mars, where the effective pressure of line formation must be well below the 0.1 atm assumed by Belton and Hunten for Venus, suggesting that his estimates are in error by less than a factor of 10.

Thus it appears not yet possible to reach a definite conclusion on the water vapor abundance, but a value less than 50 microns seems to be required to satisfy all the observations. Several tests of this conclusion are suggested in the following section. As Hunten et al. have pointed out, however, even an abundance of 50 microns is too low to permit the clouds that fill the lower atmosphere of Venus to be composed of water droplets.

4. RECOMMENDATIONS FOR FURTHER RESEARCH

It will be relatively easy to determine whether in fact the line observed near 8189 Å is a solar absorption. Additional observations of Venus with very low amounts of overlying telluric water vapor and an opposite Doppler shift should permit a search for additional members of the multiplet to which the suspected solar line belongs. In addition, such observations will provide a sensitive test for the presence of other possible Venus water vapor lines in this region. A record of the solar spectrum near 8200 Å obtained from high altitude would also aid in the problem of identifying weak solar lines ordinarily masked by strong telluric water vapor absorptions. Finally, if it would be possible to observe Jupiter with sufficient spectral resolution, the very large Doppler shift resulting from the high velocity of this planet in its orbit relative to the Earth could also be used to test for the presence of normally hidden solar lines.

It is felt that additional effort should be made to detect water vapor at other wavelengths as well. In particular, the work at 9400 Å that has been done by the present author could now be improved in sensitivity by roughly a factor of three as a result of recent modifications in the coudé spectrographs used for this work. Finally, it would be extremely useful to attempt to provide better calibrations for the observations made by Kuiper at high altitudes. This means the production of laboratory spectra of water vapor at low pressures (to 0.01 atm) with the same spectrometer that was used to observe Venus.

By removing all doubt regarding the identification of lines observed at 8200 Å and the calibration of the 1.4μ water vapor band, it will be possible to produce some hard numbers for the water vapor abundance that must be interpreted by suitable theoretical models. Observations at intermediate wavelengths can then serve as useful checks on the final result. Until such first class data are available, however, attempts to make the various abundances consistent by invoking special models for scattering in the atmosphere may be more misleading than enlightening.

5. EXPENDITURES

With the termination of the contract on July 31, 1967, the allotted funds have been exhausted.

Respectfully submitted,

IIT Research Institute

Tobias Owen

Tobias Owen
Senior Scientist

APPROVED:

C. A. Stone

C. A. Stone, Director
Astro Sciences Center